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Marine current energy devices: Current status and possible future applications in Ireland

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ABSTRACT

There is a growing demand for the use of renewable energy technologies to generate electricity due to concerns over climate change. The oceans provide a huge potential resource of energy. Energy extraction using marine current energy devices (MCEDs) offers a sustainable alternative to conventional sources and a predictable alternative to other renewable energy technologies. A MCED utilises the kinetic energy of the tides as opposed to the potential energy which is utilised by a tidal barrage. Over the past decade MCEDs have become an increasingly popular method of energy extraction. However, marine current energy technology is still not economically viable on a large scale due to its current stage of development. Ireland has an excellent marine current energy resource as it is an island nation and experiences excellent marine current flows. This paper reviews marine current energy devices, including a detailed up-to-date description of the current status of development. Issues such as network integration, economics, and environmental implications are addressed as well as the application and costs of MCEDs in Ireland.

Contents

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1. Introduction

Marine currents are generated from tidal movements and ocean circulation. Outflow of rivers and differences in temperature and salinity levels may also affect the local currents [1]. The kinetic energy contained within these marine currents can be harnessed using various technologies. The physics is similar to that of wind energy [2], where the power available at any particular site is proportional to the fluid density and the cube of its velocity [3,4]. The biggest difference between the two resources is the density of the working fluid [5]. The density of seawater is much greater than the density of air (approximately 832 times greater). Therefore the power output from a MCED is higher than a wind energy device of similar dimensions assuming similar fluid velocities [6].

The marine current energy resource has a major advantage over other renewable energy resources, as it is predictable over long time scales [7]. Grid connecting MCEDs into the electricity system should be much less challenging than other forms of renewable energy, such as wind, where the resource is unpredictable and intermittent [8].

To develop MCEDs economically, it is imperative to investigate the current velocity characteristics, reliability of overall system and the cost of electricity [9]. With market incentives and market growth, the costs associated with the technology are expected to decrease considerably. Once a potential site is identified, the type of device as well as the support structure can then be selected, depending primarily on the depth of the water column. One of the major issues restricting the development of most renewable energy technologies is grid access. Access to a reliable, stable grid would enable MCEDs to become an excellent choice as a base-load supplier, due to its predictability [10].

Marine current energy has unique characteristics with no currently foreseen impact on the environment [11]. The use of MCEDs offers a clean, sustainable approach to generating electricity. Visual aspects are not an issue, unlike other energy sources. In comparison to conventional energy sources, MCEDs offer a sustainable alternative without the effects of acid rain, climate change, radioactivity and the global contamination, which is associated with conventional systems.

Ireland has an excellent marine current energy resource. However, this resource has yet to be exploited. Ireland is heavily dependant on fossil fuel imports to meet energy demand. These limited fossil fuel reserves are continually becoming more expensive, causing a security of supply concern, while also having a negative impact on the environment. The harnessing of energy using MCEDs offers a vast and predictable energy source, suitable as a base-load electricity supply in Ireland.

2. Marine current energy extraction technology

MCEDs are used for electricity generation and can be separated into two categories [12]: rotating devices and reciprocating devices. The operation of rotating devices is similar to wind turbines used to convert the kinetic energy of the wind to electricity. Reciprocating devices consist of an oscillating hydrofoil connected to a supporting arm, which drives hydraulic cylinders and in turn a generator. Rotating devices are discussed in the following section followed by reciprocating devices.

2.1. Rotating devices

Rotating devices, known as marine current turbines (MCTs), consist of a number of blades connected to a support hub (together known as a rotor) which rotate about a horizontal axis or vertical axis. The configurations, support structures, drive systems, power regulation and generators for rotating devices are discussed below.

2.1.1. Configurations

MCTs depend on hydrodynamic forces generated by the fluid flow over hydrofoil-shaped blades to generate electricity and can be categorised as either horizontal or vertical axis [13]. Both of these device types consist of a number of blades mounted to a support, a gearbox and a generator. There is no overall agreement in the optimum shape or form of these devices. However, many of the developers favour the horizontal axis design for marine current energy extraction. Vertical axis devices have not been excluded from the on-going research and development. Horizontal axis and vertical axis MCTs are described below [14,15].

- Horizontal axis marine current turbines—Horizontal axis MCTs rotate about a horizontal axis which is parallel to the current stream [16]. The majority of the MCED devices to-date are horizontal axis MCTs. This type of MCT is classified depending on the number of blades. Multi-bladed devices are favourable as they generate greater starting torque and reduce balancing problems encountered with single-blade devices. However, hydrodynamic losses are greater with the use of a greater number of blades. Depending on turbine design, the blades can either have a fixed pitch or variable pitch to enable the turbine to operate during flow in both directions.
- Vertical axis marine current turbines—Vertical axis MCTs rotate about a vertical axis which is perpendicular to the current stream [17]. The vertical axis turbine was designed by a French engineer called Georges Jean Marie Darrieus in the 1920s. The turbine comprises of a number of hydrofoil-shaped blades mounted vertically between a top and bottom support [18]. The major problems associated with the vertical axis turbine are high torque fluctuations with each revolution and no self-starting capabilities. These issues can be reduced by configuring the blades in a helical set up as in the Gorlov rotor, illustrated in Table 1. However the helical-bladed machines have a lower efficiency than the straight-bladed design [19].

2.1.2. Support structures

The support structure of a MCT is considered a crucial component when designing the overall marine current energy system. As well as the device withstanding the harsh operating conditions, such as high marine current velocities, it is also subjected to loadings from its own weight. There are four basic support structures for MCTs [20].

- Gravity structure—A gravity structure primarily consists of a large steel or concrete base and column. It relies on its own weight to resist overturning. The seabed may need to be prepared for installation. The gravity structure consisting of steel has the advantage of ease of production, transportation and installation, but is susceptible to scouring.

Table 1
Current status of MCEDs.

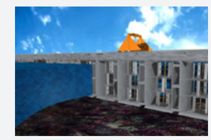
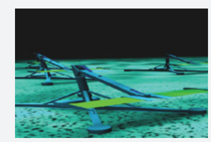
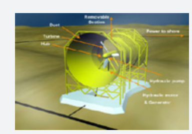
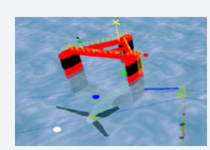
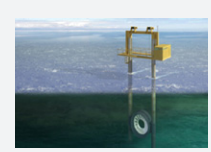
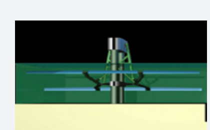
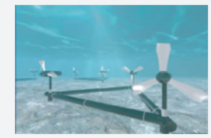
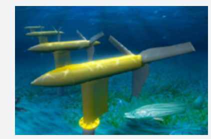
Company	Device(s)	Features	Dimensions of device	Status	Illustration
Aquamarine Power Ltd. (UK) [26]	Neptune Tidal Stream Turbine	Twin horizontal axis rotors Three-bladed design	Nothing built	The device is currently at the design stage. Testing of the device is expected to commence at the EMEC in 2011.	
Atlantis Resource Corporation PTE Ltd. (Singapore) [27]	Nereus and Solon Tidal Turbines	Horizontal axis of rotation Nereus is extremely robust Solon is a ducted deep water turbine	12 m × 4 m (Nereus) & 16 m diameter (Solon)	Nereus turbine and the Solon turbine were successfully tested in 2008.	
Blue Energy Ltd. (Canada) [28]	Tidal Fence Davis Hydro Turbine	Turbines fixed in an array known as a tidal fence Vertical axis of rotation Four-bladed design	Nothing built	The device is currently at the design stage.	
Engineering Business Ltd. (UK) [29]	Stingray Tidal Energy Converter	Reciprocating device Utilises a hydraulic generator	Unknown	In September 2002 a prototype was installed in Yell Sound off the coast of Shetland and was removed weeks later.	
GCK Technology Ltd. (USA) [30]	Gorlov Helical Turbine	Vertical axis of rotation Utilises twisted blades	1 m diameter 2.5 m high	The device was installed in the Uldolomok Strait off the coast of Korea.	
Hammerfest Strom AS (Norway) [31]	Tidal Stream Turbine	Horizontal axis of rotation Three-bladed design	20 m diameter	Installed in the Kvalsundet on the north coast of Norway in September 2003.	
Lunar Energy Ltd. (UK) [32]	Lunar Energy Tidal Turbine	Horizontal axis of rotation Hydraulic motor and generator	A proposed diameter of 11.5 m	The device is currently at the design stage. The company has agreed a £500 million deal to install 300 turbines off the coast of Korea.	
Marine Current Turbines Ltd. (UK) [33]	SeaGen	Twin horizontal axis rotors Two variable-pitch blades	2 m × 16 m diameter	Installed May 2008 in Strangford Lough, Northern Ireland and grid connected.	
Ocean Flow Energy Ltd. (UK) [34]	Evopod Tidal Turbine	Horizontal axis of rotation Moored structure Five-bladed design	1.5 m diameter	A 1/10th scale model is currently being tested in Strangford Lough, Northern Ireland.	
Open-Hydro Ltd. (Ireland) [35,36]	Open Centre Turbine	Open centre rotor and stator Horizontal axis of rotation	6 m diameter	Installed at the EMEC off Orkney in Scotland. Connected to UK national grid in May 2008.	
Pulse Generation Ltd. (UK) [37]	Pulse Tidal Hydrofoil	Reciprocating device Utilises a hydraulic generator	Unknown/nothing built	The device is currently at the design stage. In April 2008 permission was granted to deploy a prototype in the Humber Estuary in the UK.	

Table 1 (*Continued*)

Company	Device(s)	Features	Dimensions of device	Status	Illustration
SMD Hydrovision Ltd. (UK) [38]	TidEl Stream Generator	Twin horizontal axis rotors Moored structure Two-bladed design	2 m × 1.5 m diameter	A 1/10th scale model has been tested. The device is still under development.	
Tidal Energy Ltd. (UK) [39]	DeltaStream Turbine	Horizontal axis of rotation Three-bladed design	A proposed diameter of 15 m	The device is in the design stages and full production is planned for summer 2009.	
Verdant Power Ltd. (USA) [40]	Free Flow Turbine	Horizontal axis of rotation Three-bladed design	4.68 m diameter	Installed in East river New York 2007 with the intention to install an array of devices in St Laurence river from 2010–2012.	

- Monopile structure—This structure type consists of a large-diameter hollow-steel beam. The beam is driven 20–30 m into the seabed if the seabed conditions are soft or by pre-drilling, positioning and grouting if the rock is harder. The major advantage of this type of structure is that no preparation of the seabed is needed.
- Floating structure—This structure type consists of mounting the device on a floating vessel which is moored to the seabed using chains, wire or synthetic rope. This is an ideal solution for the deployment of devices in deeper water conditions.
- Tripod structure—A tripod structure is anchored to the seabed using steel piles at each of the three corners at the base of the structure. The three piles are driven approximately 10–20 m into the seabed depending primarily on the seabed conditions. This structure type is well understood due to its extensive use in the offshore oil industry. The major advantages of this structure are the reduction in structural loadings in comparison to other structures and the possible corrosion reduction due to a reduction in leg diameter.

2.1.3. Drive systems

Gearboxes are used to convert the relatively slow rotational speeds and high shaft torque to high rotational speed and low torque, which is more suitable for the generator input. Rectifying the output speed of a MCT adds mechanical complication to the overall system. An ideal gear system should be designed to work smoothly and quietly even under harsh loading conditions. For their application to MCTs, the size of the gearbox is also a critical factor. A typical gearbox may contain primary stage planetary gears and secondary two-staged spur gears to raise the shaft speed to the desired shaft output speed.

Gears are designed on the basis of duration and distribution of loads on individual gear teeth. The load distribution and duration pattern under certain marine current energy conditions need to be analysed. The results can then be extrapolated for the life-time of the gears to achieve the final design. Numerical tools can also be used to characterise the dynamic response of the MCT's gears or other linkage systems.

2.1.4. Power regulation

Power regulation is primarily achieved by positioning the blades of a MCT and is used to either limit the maximum power output, to maximise the power output or a combination of both, as well as allowing operation of the device in both directions. The power generated by a MCT is regulated by stall regulation or pitch regulation.

- Stall regulation—on MCTs consists of a number of blades attached to the hub at a fixed angle of attack (cannot be pitched). The blades are hydrodynamically designed such that when the marine current velocity exceeds the maximum operation limit the angle of attack of the hydrofoil causes the fluid flow to separate. This occurs on the side of the blade that is not facing the fluid flow. The result of this effect is a reduction in torque, and hence the power output of the device.
- Pitch regulation—requires the blades to be pitched in a way so that the power output remains constant when the designed power capacity is reached. This method actively regulates the torque generated by a MCT. These pitching systems are usually based on a hydraulic system or on electronically controlled electric motors, which pitch the blades. When the device exceeds its designed power capacity the blades can be pitched to increase the angle of attack and therefore limiting the power output. This method of regulation offers a major advantage over stall regulation due to a reduction in thrust on the device and its support structure.

2.1.5. Generators

A generator is a device which converts mechanical energy into electrical energy with the use of magnetic induction. Generators can be classified into two main categories: alternating current (AC) generators (synchronous and asynchronous) and direct current (DC) generators described below.

The synchronous generator consists of a stator containing a three-phase winding with each of the individual phases positioned 120° apart, and a rotor containing a field winding which is magnetised by a direct current. This current can either be drawn from a brush exciter, brushless exciter (a device installed on the shaft of the machine) or from the grid. The rotor is rotated by the turbine which induces voltages in the stator windings. The major advantage of a synchronous generator is the ability to control its reactive power characteristics and precise speed regulation. Therefore the use of these generators can supply reactive power rather than absorbing it. However, synchronous generators are generally more expensive than asynchronous generators.

The asynchronous or induction generator is basically a motor driven above its synchronous speed (speed of rotating magnetic field) which is basically defined by the supply frequency and the

number of poles within the motor. The stator of this generator consists of a number of wound coils placed inside its slots. They are wound for a specified number of poles depending on the speed requirement. This type of generator is not self-excited (stator needs to be magnetised from the grid), requiring an external supply to produce its magnetic flux. When the rotor is rotating faster than the rate of rotating flux it acts like a generator. The main advantage of asynchronous generators is their relatively low cost, ruggedness and self-protection against severe overloads and short circuits. The major disadvantage is the reactive power consumption and poor voltage regulation under varying rotor speed. The development of static power convertors has facilitated the regulation of the output voltage.

DC generators consist of a rotating armature which carries conductors in a magnetic field (inducing an electromotive force in the conductors), a commutator for maintaining the current in one direction through the external circuit and brushes to carry the current from the commutator to the external circuit. DC generators are relatively expensive and require regular maintenance. For offshore technologies, DC generators may well play a part due to the advantages of DC transmission (described later). However, at present, it is more popular to use AC generators and then convert to DC with solid state rectifiers than to use DC generators. Future small stand alone systems may be equipped with DC generators.

2.2. Reciprocating devices

In contrast to MCTs, reciprocating MCEDs oscillate due to the hydrodynamic lift force created by the flow over the hydrofoil [21]. Table 1 illustrates the Stingray tidal energy converter and the Pulse tidal hydrofoil, which incorporate reciprocating concepts. Reciprocating devices produce a high torque and low speed output. These devices are generally hydraulic power take-off systems utilising high-pressure oscillating rams. The high-pressure oscillating rams pressurise and transfer the high-pressure oil to drive a hydraulic motor, which in turn drives an electric generator. Secondary systems (connected to multiple hydrofoils) are required, containing many moving parts to smooth the high-pressure thrusts. This method of capturing the marine current energy is relatively expensive in comparison to MCTs. One of the major problems with this system is its overall efficiency. When the system stops at the top or bottom of the stroke it takes significant time to re-create the movement due to the hydrodynamic lift force needed on the hydrofoil surfaces.

2.3. Current status of marine current energy devices

Electricity generation from MCEDs is still in its infancy with only a few trial models being connected to a national grid [22]. Currently, the only MCEDs which have been installed and grid connected are SeaGen and Seaflow [23] (Marine Current Turbines Ltd., UK), Tidal Stream Turbine (Hammerfest Strom AS, Norway), and the scale model Open Centre Turbine (Open-Hydro Ltd., Ireland), illustrated in Table 1.

The worldwide demand for the increase in the use of renewable energy technologies to fulfill energy needs has led to major advances in marine current energy technology [24]. Table 1 provides a detailed up-to-date description of MCEDs including dimensions, features and the current status of development [25].

2.4. Main technology challenges

There are various technology challenges facing MCEDs. Some of these challenges include loadings, operation in marine environment, maintenance, and cavitation [41–43]. Below is an in-depth list of steps which need to be undertaken to address the challenges facing MCEDs:

- An in-depth resource analysis needs to be conducted to develop a better understanding of the resource and device interaction so that it delivers its predicted design performance.
- Design and manufacturing issues need to be addressed, such as turbulence and cavitation effects, the effects of increasing the size of a scaled model, manufacturing methods, etc.
- The issues with the installation of devices in a hostile environment need to be dealt with, such as foundation or mooring issues, electrical connectors, submarine cabling as well as improving network integration.
- Operation and survival problems of the device in the marine environment need to be addressed including issues such as access for operation and maintenance, biofouling, coating and sealing.
- The costs associated with the device over a life-cycle need to be identified as well as ensuring a return of investment, so that the technology is economically viable.

3. Marine current energy resource/site selection

The study of the geographical distribution of marine current flow velocities and the characteristic parameters of the marine current flow are essential for the successful application of MCEDs. Large marine currents are generally located between land masses or adjacent to headlands [44]. These narrow straits, which are the desired location for deployment of MCEDs, cause a funnelling effect, increasing the velocity of the marine current flow [45]. The velocity of the marine current flow is one of the major parameters when assessing the resource, discussed below.

The marine current energy resource can be separated into five categories [46]:

- Theoretical resource is the gross energy content of marine currents within a certain zone. This resource can be determined by modelling the marine current flow within that zone.
- Technical resource is calculated using the same method as theoretical resource, only it is limited by existing technology. This resource is based on marine current velocity, existing device efficiency and water depth.
- Practical resource is determined by limiting the technical resource. Some of these limitations include wave exposure, seabed conditions and shipping lanes.
- Accessible resource is determined by limiting the practical resource. These limitations are generally environmental in nature. A site assessment would include any possible environmental issues.
- Viable resource is determined by limiting the accessible resource. The viable resource includes commercial constraints. Marine Current Turbines Ltd. have developed a techno-economic model which determines the viable marine current energy resource as well as including costing for a particular site.

Marine current sites with a current velocity of 2.5 m/s or more are considered to have an exceptionally high energy resource [47]. From previously conducted assessments the major marine current energy sites are located in the following [48]:

- The Amazon.
- The Arctic Ocean.
- The Bay of Fundy.
- Bosporus.
- The English Channel.
- Gibraltar.
- The Gulf of Mexico.

- The Gulf of St Lawrence.
- Hebrides.
- The Irish Sea.
- Messina.
- Rio de la Plata.
- Sicily.
- Skagerrak-Kattegat.
- The Straits of Magellan.

4. Network integration

The network integration issues associated with MCEDs are similar to onshore renewable energy technologies, such as stability losses and reactive power compensation. The installation of submarine cables is well understood in the offshore oil and gas industry. Network integration can be separated into three divisions: transmission, grid connections and submarine cables.

4.1. Transmission

The electricity generated by MCEDs needs to be transmitted to the mainland. This electricity needs to be stepped up to a higher voltage to minimise transmission losses. The size of the step-up transformer is dependant on the distance from the shore and the power capacity of the marine current system. There are two different options available to achieve offshore electrical power transmission: high voltage alternating current and direct current alternating current.

4.1.1. High voltage alternating current

Current and voltage are the two major influencing factors of electrical power transmission. AC has been regarded as the best choice for electrical power transmission using the high voltage alternating current (HVAC) system. The HVAC system basically transmits electrical power as AC at a high voltage. This type of transmission system is a mature and reliable technology. The HVAC system is the most widely used transmission system to transport electrical power. A HVAC system generally contains the following [49]:

- An AC collecting system at the MCED.
- An offshore substation containing transformers and reactive power compensation.
- A three-phase submarine cable.
- An onshore substation containing transformers and reactive power compensation.

4.1.2. High voltage direct current

The use of the high voltage direct current (HVDC) system has become an economical alternative to HVAC for transmitting electrical power over large distances [48]. This system offers the ability to transmit electrical power as DC at a high voltage. Many of the stability issues associated with connecting offshore devices to the grid have been resolved with the use of the HVDC system. A HVDC system generally contains the following [50]:

- Transformers.
- AC to DC converters.
- DC current filtering reactance.
- DC cable.
- DC to AC converters.

4.2. Grid connection

As with most renewable energy technologies, MCEDs require access to a reliable power grid near the site, so that the electricity generated can be fed in [51]. Renewable energy technologies, especially MCEDs, offer an ideal base-load supplier. Electricity demand varies with time throughout the day, with peak demand occurring at certain intervals. Matching supply with demand is an important aspect of the integration of renewable energy technologies. Marine current energy has the advantage of being predictable and reliable, unlike other renewable energy sources.

For economic exploitation of marine current energy, a reliable grid is essential. Poor grid stability can result in significant losses; this deficiency could limit the generating capacity of even the major identified sites [52]. This will become more critical if the penetration rate is high. For MCEDs load demand is never near the renewable resource, and therefore, transmission losses are unavoidable. A decision also needs to be made if deep reinforcement is required instead of a shallow connection. The deep reinforcement is basically the additional hardware required to the downstream network as a consequence of adding the extra generation capacity.

A definitive time period is required for starting the generators and synchronising with the grid. The fluctuations in the load can be predicted beforehand; therefore a decision can easily be made as to what system is utilised at any given time. The use of asynchronous generators on MCEDs may place a strain on the grid. Asynchronous generators, instead of supplying reactive power to the grid, absorb reactive power from the grid. It is already known from wind turbine technologies that low frequency operation also affects the output power into the grid, as the output frequency has to be maintained relatively close to 50 Hz [53].

4.3. Submarine cables

The use of submarine cables is well understood due to their use in the offshore oil and gas industries. The type of cable used affects the cost and installation of the system. The fundamental structure of a submarine cable consists of a conductive core, which is a circular section formed with treaded wires carrying the current. For medium and high voltage applications the material used is copper, although, sometimes aluminium is used but it is not as efficient [48]. The cable also consists of electrical insulation which is characterised by the material; either oil impregnated paper or extruded plastic. The use of alternative cross-linked polyethylene cable in submarine cable looks promising. It is cheaper to manufacture, has better bending properties, higher mechanical resistance and lower in weight than other cables [54].

Another of the major issues associated with submarine cable installation is the decision to bury or lay the cables on the sea floor. The cost of installation can be greater than the cost of the cable in some cases. Special machines are necessary for installing these cables; these machines are able to operate at depths of 1000 m. The MCED needs to be connected to the cable lying in the seabed, whether it is a floating structure or a fixed structure. For floating structures the cable itself is not capable of withstanding the loads it will be subjected to. J-tubes, which are conduits that extend down with large bends to the seafloor, offer protection to the cable.

5. Economics of marine current energy devices

5.1. Methods for establishing the cost of generating electricity

There are three different ways of expressing the cost of a MCED: the cost per rated power of the device (cost/MW), the cost per unit size of the device (cost/unit area), and the cost per unit of electricity generated (cost/kWh). The simplest way to express the cost of a MCED is the cost per rated power. The basic method for calculating this cost accounts for the following:

- Capital costs which can be separated into device and site-specific costs and are once-off costs applicable to the development of a new marine current energy farm. The device costs are made up of the turbine costs, structural costs, electrical machinery costs, control systems costs, foundation or mooring costs, cabling costs, delivery costs and assembly costs. The site-specific costs consist of design and specification costs, grid connection costs, cabling costs, installation costs, permits and permissions costs and commissioning costs.
- Running costs which are made up of the operation and maintenance (O&M) costs. These are annual running costs made up of servicing, insurance, telecommunications, taxes and administration.
- Financing which is the cost of repaying loans from banks and investors. Loan repayments may be required and if the project is partly financed by an investor they may also demand a return on their investment.

For MCEDs there are no fuel costs as the resource is free. When the capital costs are paid off the only ongoing expenses are running costs. As the market grows it is expected (as with other renewable energy technologies) that the capital costs of MCEDs will fall considerably. This potential reduction in capital costs can be predicted with the concept of learning curves. A learning curve gives an empirical relationship between the cost of an item as a function of the cumulative volume of the items produced. This cost reduction trend is not noticeable at present due to the current stage of development of MCEDs.

The basic method of calculating the cost as described above is not the most accurate method. The most accurate method of calculating the cost per rated power is life-cycle costing (LCC) which is a commonly used method of evaluating the economics of energy technologies. The LCC method incorporates all the expenditures and revenues over the life-time into a single cost so that the technology can be economically assessed. An equation for calculating the LCC of any particular energy technology is given as [55]:

$$\mathrm{LCC} = C_{\mathrm{pv}} + M_{\mathrm{pv}} + F_{\mathrm{pv}} + X_{\mathrm{pv}} - S_{\mathrm{pv}} \tag{4}$$

where

- C_{pv} is the capital cost of the total technology which is considered as a single payment occurring in the initial year of the project, regardless of the finance conditions.
- M_{pv} is the O&M costs on a yearly basis, including salaries, inspections and insurance.
- F_{pv} is the yearly fuel costs.
- X_{pv} is the external costs which includes damage cost and damage prevention.
- S_{pv} is the salvage value of the technology in its final year of life-time.

The cost per rated power is obtained by dividing the cost calculated using one of the above methods by the rated power.

The above way of expressing the cost of a MCED (cost per rated power) can be misleading as the rated power of a MCED is a function of the design marine current speed. The cost per unit size is a better way of expressing the cost of a MCED. The cost is calculated using either the basic method or the LCC methods described above. The cost per unit area is obtained by dividing the calculated cost by the appropriate area.

However we are often more concerned with the cost of generating a unit of electricity and, therefore, the cost per kWh is a much better way of economically assessing the cost of a MCED. Generating electricity using MCEDs is economically viable if the cost of generating electricity per unit is less than the tariff available [56]. The selling price of electricity depends not only of the cost of generation, but also on various other factors which affect the market such as taxes [57].

An excellent method to calculate the cost per kWh is to calculate the levelised energy cost (LEC). A LEC is basically an economic assessment of the costs associated with generating electricity over a certain time scale. This method expresses the costs that occur at irregular intervals as equivalent equal payments at regular intervals. This method expresses the LCCs as equal annual repayments. A LEC is calculated as the annual LCCs divided by the annual electricity generation and is simply defined as the cost of energy (unit cost/kWh). A LEC comparison is often used to compare emerging energy technologies against those already in widespread use.

There are various reasons to use this method of cost comparison rather than comparing the capital cost of each technology. This way allows the evaluation of all the costs associated with installing and operating any power plant over its life-time. It enables a realistic assessment of the LCC of the technology thus allowing a comparison of different energy technologies. For example, MCEDs may have a higher capital cost than gas turbines; however they require no fuel, less maintenance and have substantially less external costs (see below).

The Carbon Thrust, an independent company set up by the UK government in 2001 with the objective of helping the move to a low carbon economy and develop clean renewable technologies, compiled a report in 2005 in which it is claimed that the cost of electricity generation from MCEDs in the UK will be approximately 7 p/kWh based on a LEC analysis. This value takes into account the use of the sites with the best viable resource. The cost of electricity generation is then expected to fall to approximately 3 p/kWh once 3000 MW of capacity is installed. Fig. 1 illustrates the LEC of electricity generation in the UK using different technologies based on figures published by the Royal Academy of Engineering, the UK's national academy of engineering.

External costs also need to be taken into consideration when determining the total cost of generating electricity. These costs include the costs to human health and the environment which can also be referred to as social costs. Social costs get its name from the fact that society bears the costs of pollution in terms of poorer health [59]. This leads to higher health service costs which are paid for by the tax payer, a degraded environment and an increase in the cost of food. However, no method has been formulated and accepted to calculate the true price of social costs. The life-cycle emissions from the generation of electricity from MCEDs depend primarily on the countries heat and power mix during the manufacture and installation of the device. It is expected that the environmental impacts will be proportional to the emissions produced by electricity generation [60]. The significant contributors from the combustion of fossil fuels causing these damaging effects are nitrogen oxides, total suspended particulate, carbon dioxide and to a lesser extent sulphur oxides. The external costs need to be determined in order to effectively compare the cost per kWh generated from conventional systems with the cost per kWh generated from MCEDs.

5.2. Cost analysis of a marine current turbine farm

The LCCs have been estimated in a report published by the Department of Trade and Industry in the UK entitled *Economic Viability of a Simple Tidal Stream Energy Capture Device* for a fixed and variable-pitch horizontal axis MCT power plant of 30 turbines, each of 1 MW capacity and consisting of two rotors per support structure, over a life period of 25 years. These are shown in Table 2 below.

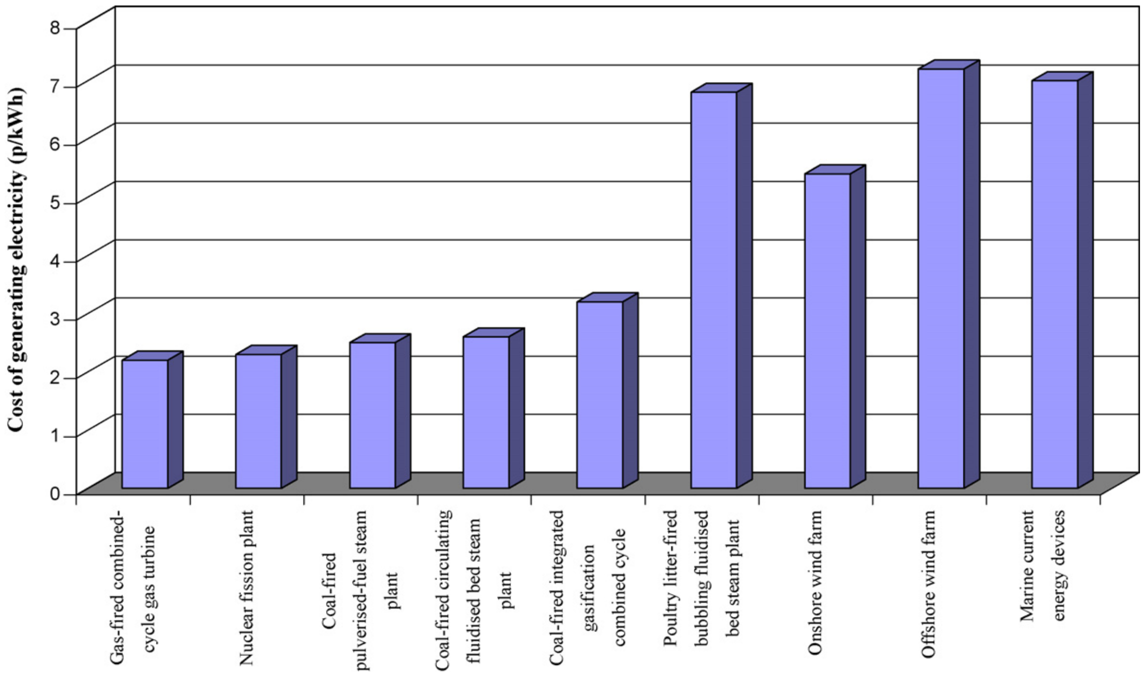


Fig. 1. LEC comparison of generating electricity using various technologies excluding the cost of CO_2 emissions [58].

The cost of grid connection was estimated at £120,000 MW^{-1} capacity in the UK. However the cost of grid connection could vary depending on the size of the system and location.

According to these estimates the LECs over a 10-year period are £119 MWh^{-1} and £129 MWh^{-1} for the fixed pitch and variable-pitch MCT power plant respectively. These costs reduce to £94 MWh^{-1} and £104 MWh^{-1}, respectively, over a 15-year period. It can be seen that over a greater life span the cost of electricity generation reduces significantly [61].

The O&M costs depend primarily on the number of MCTs installed at a site. These costs can be relatively expensive in comparison to other renewable energy technologies but are comparable to offshore wind farms due to the following:

- MCEDs can only be accessed at periods of calm sea conditions.
- Weather and sea conditions may also determine the ease at which replacement of components can be conducted.

Presently the only proven configuration for MCEDs is the horizontal axis MCT. The cost of electricity generation using MCEDs is relatively high in comparison to conventional generating systems. However these costs should be considered in the following context [62]:

Table 2
A 25-year LCC estimate for a marine current turbine power plant in 2007 [55].

Cost item	Fixed pitch	Variable pitch
Initial cost set up	£3,750,000	£3,750,000
Offshore equipment	£4,500,000	£4,500,000
Onshore equipment	£2,250,000	£2,250,000
Mounting	£4,500,000	£4,837,500
Line replacement unit	£22,500,000	£24,187,500
Routine O&M	£14,381,276	£15,455,078
Unscheduled servicing	£108,850	£116,560
Annual running costs	£4,090,674	£4,090,674
De-commissioning (/unit)	£750,000	£750,000
Total	£56,830,800	£59,937,312
LCC (cost/MW)	£1,894,360	£1,997,910

- The relatively high costs of electricity generation due to the early stage of development. It is then expected that these costs will decrease as they did with other technologies with time.
- The size of the projects will have an impact on the cost of the technology. It is known that all technologies cost more when deployed on a small scale; this is especially true for MCEDs.
- Installation systems are under-developed. The development of these systems will allow the second generation of systems to be deployed in deeper water and on a larger scale.
- The unit costs will apply over the period of the financing. Once the capital costs have been paid off the generating costs will reduce; therefore, the cost of generation in later years permits relative low generating costs.

6. The application of marine current energy devices in Ireland

6.1. Available resource

Ireland is the most energy import dependant country in the European Union. In 2006, Ireland's energy import dependence reached 91% with an energy consumption primarily achieved by the combustion of fossil fuels. The energy consumption reached 13.011 million tonnes of oil equivalent, with the use of fossil fuels accounting for 96% of the energy consumed. An Irish government white paper entitled *Delivering a Sustainable Energy Future for Ireland* was published by the Department of Communications, Marine and Natural Resources on the 12th March 2007. This government white paper is driven primarily by the challenge of a secure energy supply and the prevention of climate change.

The deployment of renewable energy technologies offers a method of increasing the security of energy supply, reducing environmental impacts and developing innovation and promoting business. In recent years there has been an increasing interest in offshore renewable energy technologies in Ireland [46]. Ireland has an excellent theoretical marine current energy resource. However this resource is limited by practical, accessible and viable constraints. A report compiled by Sustainable Energy Ireland, an organisation set up by the Irish government with the objective of

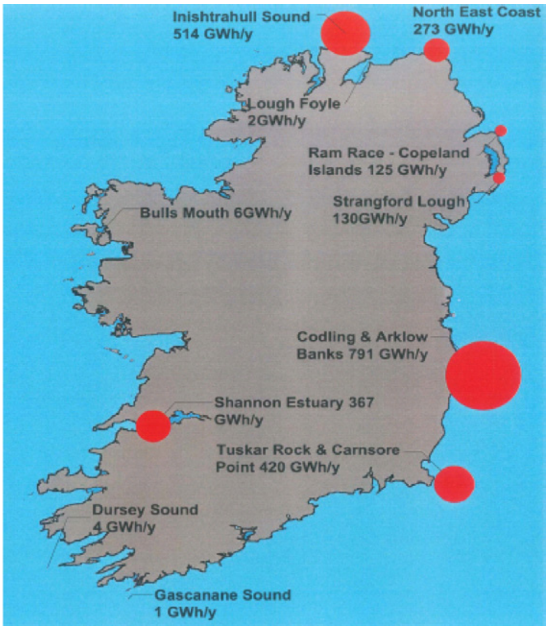


Fig. 2. Practical marine current energy resource in Ireland [46].

promoting and assisting in the development of sustainable energy systems, in 2004 entitled *Tidal and Current Energy Resources in Ireland* identified the sites which have cost effective potential to exploit marine current energy in Irish waters.

The marine current energy sites which contain the greatest potential are primarily located in the St. Georges and North Channels and along the east coast of Ireland. These marine current sites are generally located between land masses or they largely influenced by the local geometry of the seabed. The marine currents around Ireland have been modelled using a 2D flow model developed by a company called RPS Kirk McClure Morton in the UK. The results of this model were used to identify the theoretical marine current energy resource around Ireland and subsequently the practical resource was identified. The practical marine current energy resource thus obtained for Ireland is shown in Fig. 2.

The viable energy resource for each of the above sites was calculated by applying the relevant limitations. The techno-economic model, developed by Marine Current Turbines Ltd. (UK), was used to determine the viable resource at the various practical resource locations. The viable marine current energy resource for Ireland has been estimated as 0.915 TWh/year [63], based primarily on the principle that sites with a marine current velocity of less than 2 m/s are excluded [46]. Fig. 3 illustrates the viable marine current energy resource sites along the coast of Ireland.

6.2. Costs associated with the deployment of a marine current energy farm in Ireland

As discussed previously, the capital costs associated with the development of a marine current energy farm can be separated into device and site-specific costs. The main site-specific costs associated with the development of these devices in Ireland include:

- Grid connection costs—which include transmission lines, switch gear and infrastructure required to connect a marine current energy farm to the Irish grid. The cost of grid connecting a MCED farm is dependant on plant generating capacity, connection voltage, distance the farm is from shore and the number of connections required. The application cost for grid connecting a 30 MW MCED farm in Irish waters is €63,676 excluding VAT payable to Ireland's electricity supply board, ESB networks. In Ireland the cost to grid connect a MCED farm is expensive, typically 25% of the investment cost. The grid connection options available in Ireland are 38 kV, 110 kV (both HVAC) and HVDC connections. The type of connection depends primarily on the size of the project and the distance from shore. The 110 kV connection is expensive, with costs in the region of €15–25 million for this MCED farm [66]. A 38 kV double connection offers an attractive alternative to the 110 kV connection, as it is less expensive. However, electrical losses are considerably less with the use of a higher voltage connection.
- Permits and permissions costs—which are the costs associated for the preparation and the application of the various permits required for the deployment of MCEDs. When the suitable sites and technology are selected, permissions and permits are required for progression. In Ireland there are several permissions required, which can be a long and laborious process. A permit is required from the National Heritage Service of the Department of Arts, Heritage, Gaeltacht and the Islands. A permit is also required to construct an electricity generating station, generate electricity and to supply electricity from the Commission for Electricity Regulation. Planning permission is required from the

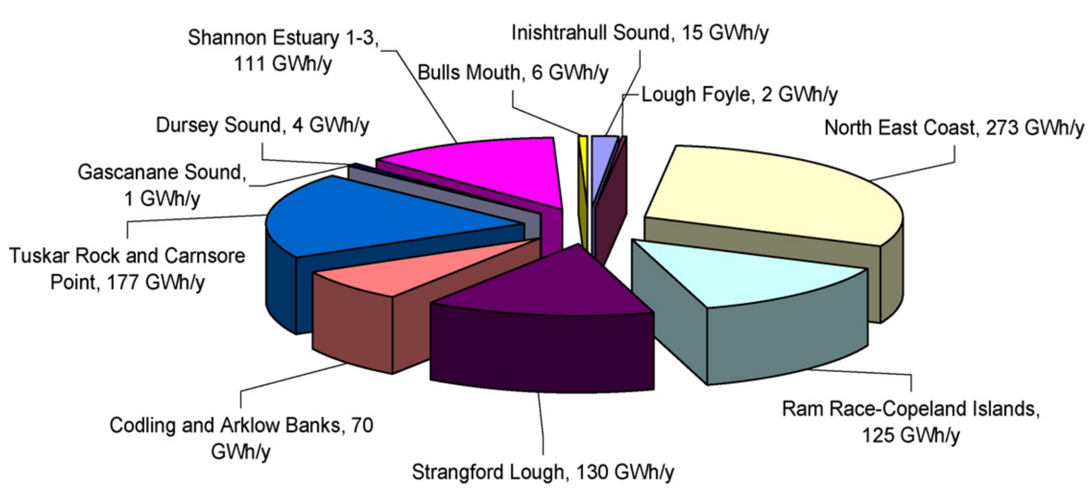


Fig. 3. Viable marine current energy resource in Ireland (GWh/year) [64,65].

Local Government Planning Authority. Permission is also required for the installation of submarine cables from the Department of Marine and Natural Resources.

6.3. Marine current energy devices currently operational in Irish waters

Installed in Irish waters is one of the best known and largest marine current energy devices worldwide known as SeaGen, which is being developed by Marine Current Turbines Ltd. (UK). The company installed the worlds first MCED at Loch Linnhe in Scotland in 1994 followed by Seaflow, a 300 kW device which was installed off Lynmouth in Devon in May 2003. SeaGen was installed in Strangford Lough in Northern Ireland and grid connected in May 2008. The device reached its full power capacity of 1.2 MW in December 2008.

In parallel, an Irish-based company called Open-Hydro Ltd. is currently testing a scaled model of their device called the Open Centre turbine. The device is installed at the European Marine Energy Centre (EMEC) and in May 2008 was connected to the UK national grid. A 1 MW turbine will be installed in the Bay of Fundy as part of Nova Scotia's tidal energy test facility before the end of 2009.

6.4. Future potential

With the development of marine current technologies, other sites will become available along the coast of Ireland where exploitation was previously uneconomical. Currently the devices could be installed in several sites along the east coast and along the Shannon Estuary. Marine current energy could play a valuable part in Ireland's future energy supply, as it is a pollution free and a sustainable alternative to the combustion of fossil fuels [67].

7. Implications of energy extraction using marine current energy devices

MCEDs are considered the most environmentally benign of all tidal energy extraction technologies [68]. These devices are regarded as environmentally friendly; however, they are not free from emissions entirely. The production of the each of the parts, the resourcing and the transport of the materials requires the consumption of energy. Therefore emissions are produced as long as these energy resources are based on fossil fuels [69–74].

Public acceptance of MCEDs is likely to be high due to zero visibility and zero audible noise. Unlike tidal barrages, MCEDs do not block bays or estuaries, interrupt fish movements or alter hydrology [51]. They also offer a relatively large potential of generating capacity without the extreme effects on the ecosystem which would be encountered with the use of a tidal barrage.

Recent research in tidal energy extraction is focused predominately on marine current energy extraction which utilises the marine current flow rather than the range in height of the tides. These MCEDs can be situated in areas where they do not affect the migration of sea mammals and fish. The movement of the blades or hydrofoils of the devices are expected to be slow enough to reduce fish mortality.

When considering the deployment of MCEDs the following potential issues need to be considered:

- Marine mammals may come into contact with these devices with possible collisions. This issue is being investigated for installation and operation of the devices, as well as other offshore devices.
- The effects on fish may be negative or positive. In terms of fisheries the structure and the cabling may have an effect on fish stocks and their habitats.
- The effect the MCED may have on the area in which it is installed.
- Underwater archaeology. A full assessment of the site may be required before the device can be installed.
- The effect on recreational activities.

The major environmental effect of MCEDs in terms of pollution is the use of hydraulic systems. Some of the devices described earlier use hydraulic systems to generate electricity. The potential leakage of hydraulic oil would be detrimental to the surrounding environment.

8. Conclusion

Marine current energy has the potential to play an important role in the future energy supply in many countries around the world. The resource has various attractable characteristics such as predictability.

The generation of electricity using MCEDs is still in its infancy. The only MCEDs which have been installed and grid connected to-date are Seaflow and SeaGen (Marine Current Turbines Ltd., UK), Tidal Stream Turbine (Hammerfest Strom, Norway) and the scale model Open Centre Turbine (Open-Hydro Ltd., Ireland). The successful installation and operation of these devices has sparked interest from various countries to utilise this abundant energy source.

To develop marine current energy it is imperative that the costs are at a minimum so that it is economically viable. However there are various issues which need to be addressed to assist the development of MCEDs including design and installation challenges, maintenance, electricity transmission and environmental impacts.

Ireland has an excellent marine current energy resource. There are several sites identified as economically viable for commercial scale generation. However, there are numerous other sites which are not economically viable due mainly to the marine current velocity being less than 2 m/s. As the technology is developed it is expected that energy extraction from these presently unviable sites will be economically viable in the future.

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